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DATA-DRIVEN RESEARCH ON BELT CONVEYORS ENERGY EFFICIENCY CLASSIFICATION

The issue of energy efficiency in belt conveyors aligns with the current trends of energy saving in mining, driven by sustainable development goals and European legislation. The topic of energy-efficient conveyor transport faces the challenge of objectively assessing the energy efficiency of belt conveyors. The presented article demonstrates an analysis of the energy efficiency of belt conveyors in a lignite open-pit mine. As part of the research, the energy consumption of conveyors operating in a transport system was compared using the parameter of electrical energy consumption and the specific energy consumption (SEC) index, highlighting significant parameters affecting its interpretation. Based on the values of the modified lifting resistance SEC index, and the volume of transported material, observations were divided into groups reflecting energy efficiency classes using a k-means algorithm. The research shows that a proper assessment of the energy efficiency of a belt conveyor should consider the amount of transported mass concerning the maximum capacity, the conveyor's design parameters, and the working environment characteristics.

Keywords: Energy efficiency; energy consumption; open-pit mining; belt conveyors

1. Introduction

In the mining industry, belt conveyors are vital transportation systems for conveying materials across long distances within mining sites. They can transport large volumes of material and enable its continuous flow. Integrated with automation and control systems they contribute to the overall efficiency of the transportation process and its safety [1-3]. Moreover, belt conveyors require relatively low maintenance and have lower operating costs compared to other transportation

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methods, such as trucks or rail systems. They also contribute to environmental sustainability by reducing emissions and fuel consumption compared to truck haulage systems [4-6]. The example of a belt conveyor working in the open pit mine is presented in Fig. 1.

Fig. 1. The example of working belt conveyor in the open-pit mine (*Source:* private archive)

However, considering belt conveyors systems themselves, one of the main scopes to achieve is their electrical energy consumption reduction [7,8]. It was recognized that conveyors consume electrical energy that accounts for up to 50% of total consumption in mine [9]. Another research shows that, in a typical South African gold mine around 23% of the total operating expenses would be allocated to electricity costs [10]. Numerous industrial applications and innovative solutions focus on optimising and reducing electrical energy consumption while meeting performance and reliability requirements [11,12]. Considering the POET perspective [13], (POET is an abbreviation for performance, operation, equipment, and technology) efforts towards energy-efficient conveyor transport are carried out in the following areas:

- equipment efficiency – issues related to reducing the resistance of belt conveyor movement through the appropriate selection of conveyor components such as belts and idlers [14-16], improving the efficiency of the drive system [17,18], or optimising multi-drive systems [6,19];
- operation efficiency – issues related to organising operations aimed at increasing the utilisation rate of conveyor transport capacity by speed control strategy – the adjustment of belt speed based on the material flow rate [20] or coordination subsystem cooperation with the use of accumulative bunkers [21] or virtual energy storage approach [22];
- technology efficiency – issues related to modelling energy consumption considering transport capacity, belt speed, and various operating conditions of the conveyor [23] among which dynamic models are considered to be the most valuable for analysing mechanical behaviour of belt under non-uniform distribution of bulk material [24], and the utilisation

of the latest technologies indirectly impacting the improvement of energy efficiency of belt conveyors e.g. monitoring and diagnosis of belt conveyors with the use of magnetic technology for example [25];
- performance efficiency – issues related to the measurement of the global system performance, assessed through external but deterministic indicators such as amount and cost of consumed or saved energy or environmental footprint e.g. total particle emission [26,27].

It should be emphasised that a key challenge in terms of energy efficiency is the reliable assessment of the effects of actions aimed at reducing energy consumption [28]. It is pointed out that the assessment should focus on the rational use of electrical energy by indicating the achieved effect (such as transporting material over a specific distance) in relation to the amount of electrical energy supplied [29].

Currently, the assessment of the energy efficiency of belt conveyors, specifically its improvement, is conducted individually under specific operating conditions using the so-called comparative method [6,30]. Its main idea involves comparing existing conveyors with newly designed ones, modernised ones or virtual ones (digital twin technology) [27,31-33]. Even though this method yields valuable results, there is still a need to introduce the approach that allows for a universal and reliable assessment of belt conveyors' energy efficiency. Therefore, one of the proposals is to introduce a comprehensive approach to standardising the energy efficiency of belt conveyors, thereby enabling users to make a credible assessment of the transport solution applied in specific working conditions [34].

Developing a method for assessing and classifying the energy efficiency of belt conveyors based on their mechanical construction and proper usage is an action that supports energy and environmental policies, helping to achieve sustainability goals [35-37]. Involving literature reviews about energy consumption in the mining industry [38-40], GRI reporting guidelines (GRI stands for Global Reporting Initiative) [41], and EU regulations on energy efficiency [42], a scheme describing and relating to energy efficiency in the mining industry was developed (Fig. 2).

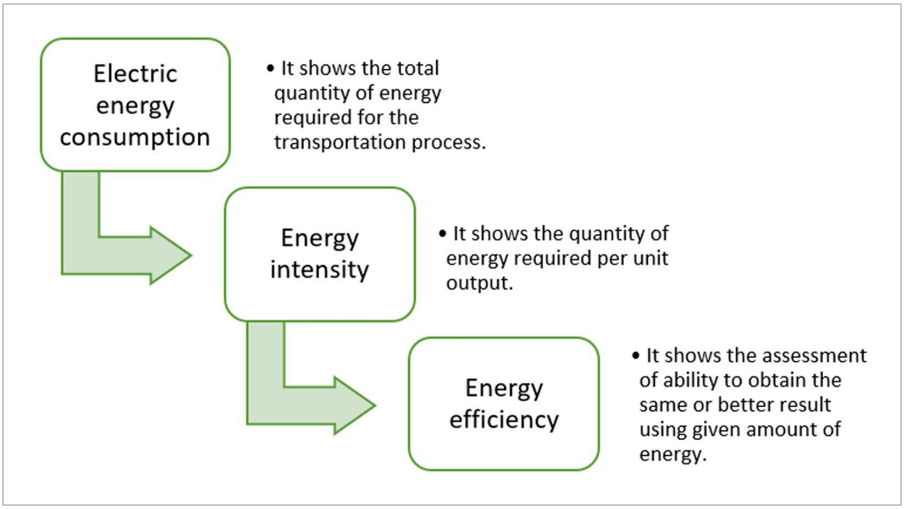


Fig. 2. Scheme of energy efficiency assessment attitude

The paper aims to present an idea of the approach for assessing the energy efficiency of belt conveyors by determining energy efficiency classes. The study uses real data to discuss the usefulness of electric energy consumption parameters and specific energy consumption indexes for belt conveyors' energy efficiency assessment. The last part of the research introduces the energy efficiency classification pointing out the importance of operational efficiency and setting recommendations for further research.

2. The assessment of belt conveyors energy efficiency

The assessment of belt conveyor energy efficiency was performed for 6 conveyors (OA-OF) that have the same capacity and operate in an open pit mine as a continuous system used for overburden transportation. The advantage of the considered system is that conveyors are the same when it comes to belt width and belt speed while differentiated in terms of technical parameters (TABLE 1) while transporting the same value of the material. Considering transportation systems allows us to compare the operation, construction, and technical condition of conveyors, as well as assess their energy efficiency.

TABLE 1

Belt conveyors parameters

	OA	OB	OC	OD	OE	OF
						
Length, m	370	562	1590	773	732	802
Inclination angle, °	6.61	0.50	-0.50	0.00	1.00	0.00
Installed power, kW	3000	1890	2520	2000	1890	2000
Power installed per meter, kW/m	8.1	3.4	1.6	2.6	2.6	2.5
Belt type*	ST 3150	ST 2000	ST 3150	ST 2000	ST 2500	ST 2500

* ST stands for steel-cord belt type, while numbers 3150, 2000 and 2500 describes nominal belt strength

2.1. Analysis of the electric energy consumption

The analysis was carried out for data collected within the whole year. Calculations show that the transportation system used around 30.5 GWh to transport 15.17 mln m^3 of overburden. The transportation system used daily around 106 MWh on average. It is important to note that the ascending OA and descending OC conveyors consumed more than 40% of the total energy (Fig. 3). The variance between their total energy consumption amounts to approximately 29 MWh. Based on the boxplots that present daily electric energy consumption distribution for different conveyors (Fig. 4) two groups of conveyors can be indicated: low and high energy efficient. The first group can be represented by OA, OC and OF conveyors while the second one by the others.

Due to the significant correlation between electricity consumption and the volume of transported material, the power regression model was adjusted for the analysed data (Fig. 5 and TABLE 2).

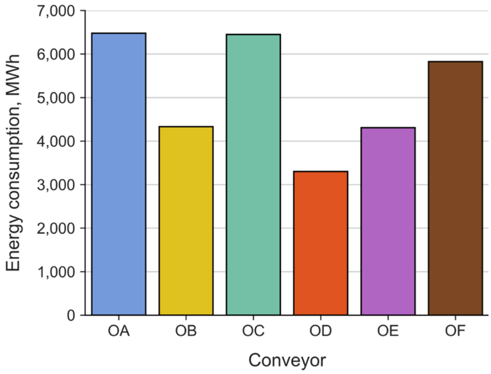


Fig. 3. Total electric energy consumption for OA-OF conveyors

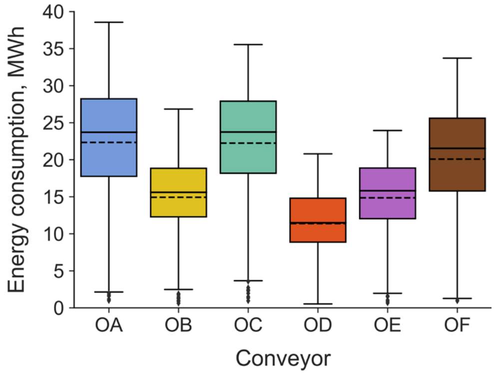


Fig. 4. Distribution of daily electric energy consumption for OA-OF conveyors, where dashed line shows mean value

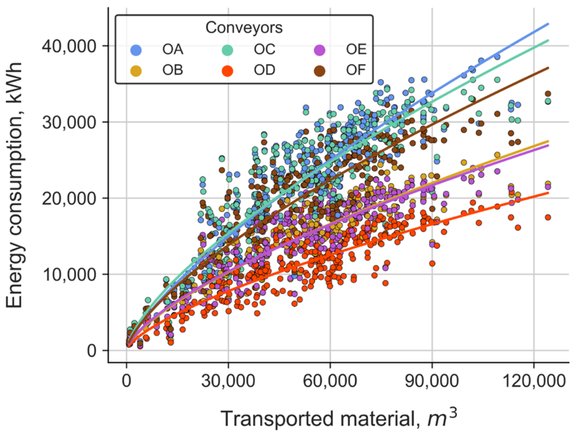


Fig. 5. Relationship between daily electric energy consumption and the volume of transported material

TABLE 2

Power regression model fit measures for OA-OF conveyors

	OA	OB	OC	OD	OE	OF
R^2	0.79	0.76	0.78	0.72	0.77	0.77
MAPE	15.67%	17.18%	16.81%	20.37%	16.50%	16.56%

* MAPE stands for Mean absolute percentage error

Generally, the results show that an increase in the transported material leads to higher electricity consumption. However, considering the characteristics of the continuous system and its working conditions it can be noted that parameters of the belt type, conveyor route profile (length and angle of inclination) and drive parameters (installed power per metre) must have a significant impact on belt conveyors energy efficiency.

For instance, for the conveyors consuming the most electrical energy, namely OA and OC which operate with the same belt, noticeable differences are observed in their length and the height of the belt and material lift/drop. It means they are completely different in terms of the distribution of individual components of motion resistance, especially secondary (concentrated) resistance and lifting resistance. The conveyor's OD and OE are conveyors of nearly the same length; however, the former is a horizontal conveyor, and the latter is an inclined one (lifting height of approximately 13 metres), which results in differences in the energy they consume. Similar amounts of energy are consumed by OB and OE conveyors despite differences in their technical parameters, such as length, lifting height (the lifting height for conveyor OB is approximately 5 metres), and installed power per metre of conveyor length.

The quantity of electric energy consumed provides important input for energy efficiency assessment, but it alone is not sufficient. The electric energy consumption indicator is influenced by factors such as the effectiveness of the process, technical specifications and design of the components, and any potential energy losses. Simply measuring the quantity of electric energy consumed does not capture the full picture of belt conveyors' energy performance.

Therefore, to assess the energy performance of the conveyors, the next part of the work uses the Specific Energy Consumption (SEC) index that allows for individual evaluation of belt conveyors' energy intensity in relation to the performed transportation task.

2.2. Analysis of the specific energy consumption

The Specific Energy Consumption (SEC) index is closely related to the conveyor's resistance to motion, the efficiency of the drive system, and the amount of material being transported. As shown in [31,43] SEC is the fundamental measure of the conveyor systems operational quality and is expressed by the following formula:

$$SEC = \frac{E}{M \cdot L} \quad \left[\frac{\text{Wh}}{\text{kg} \cdot \text{m}} \right] \tag{1}$$

where:

E – consumed electric energy, Wh;
M – the amount of transported material (optional for a homogeneous load – volumetric measure), kg or m^3;
L – the length of the conveyor, m.

Analysis of the SEC index expressed in Wh/m^4 revealed that the average daily value of the index for the considered transport system was 0.48 Wh/m^4. Data presented in TABLE 3 and Fig. 6 indicates that the greatest level of SEC values dispersion around the mean is observed for the OD conveyor. It was noticed that the highest values of the SEC index are achieved by the OA conveyor – the uphill conveyor, while the lowest by OC and OD conveyors (downhill and horizontal conveyors respectively). Based on the SEC value distribution (Fig. 6) three groups of conveyors can be indicated: low, medium, and high energy efficient. The first group can be represented by OC, and OD conveyors, the second one by OB, and OF conveyors, and the last one by OA conveyors. The values of the index confirm that the key parameters for energy efficiency are the design parameters of the conveyors operating in the analysed transportation system.

TABLE 3

Daily statistics of the SEC index (in Wh/m^4) for OA-OF conveyor belts

	OA	OB	OC	OD	OE	OF
Mean	1.28	0.58	0.31	0.32	0.45	0.55
Median	1.20	0.52	0.28	0.28	0.40	0.49
Coefficient of variation	37%	49%	51%	56%	53%	47%

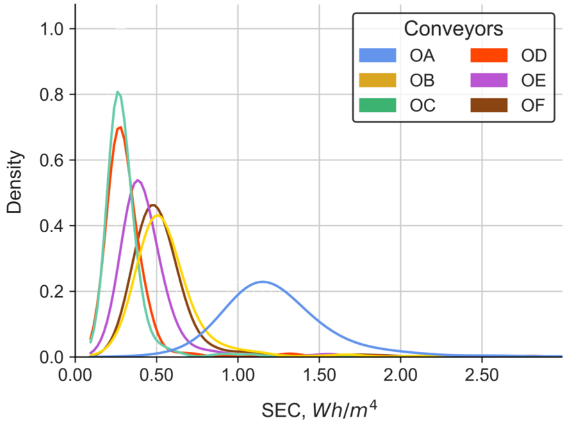


Fig. 6. The probability density function of specific energy consumption index for analysed belt conveyors

Based on the data, a graph depicting the daily energy efficiency index as a function of the daily transported volume for individual conveyors was prepared – Fig. 7. The graph shows that the energy consumption index decreases with an increase in the amount of transported material. For a small volume stream, a sharp drop in the index value is observed, which then stabilises. An important aspect here is not only the quantity of transported material but also the degree of utilisation of theoretical efficiency – as demonstrated in references [29,44]. Therefore, as the efficiency of the conveyor increases along with the level of utilisation of installed power, the energy consumption coefficient will decrease with its increase. Thus, it is important to manage changes in the transportation system load so that conveyors utilise the transport potential to the maximum extent possible.

Furthermore, it is observed that the value of the electric energy utilisation index decreases with:

- an increase in the conveyor length,
- a decrease in the angle of inclination of the conveyor route, and
- a decrease in the installed power value per metre of conveyor length.

This is because secondary (concentrated) resistances do not depend on the length of the conveyor and are only generated in specific locations; the resistance of lifting the material constitutes the main component of the resistance to motion of the ascending conveyor; conveyor drive units are often oversized because they are designed with a certain margin allowing operation in difficult conditions [43,45].

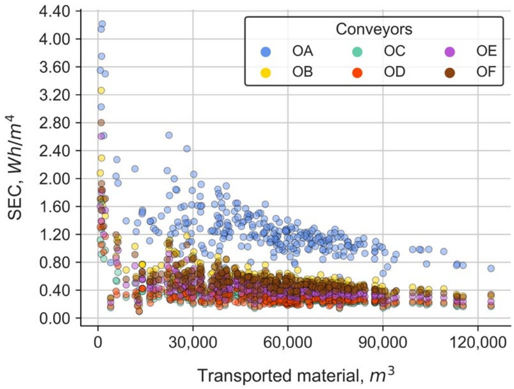


Fig. 7. Relationship between daily specific energy consumption index and the daily transported amount of the material

Additionally, in the case of data analysis for an open-pit mine, atmospheric conditions can be significant for the value of the SEC index. Since operational data comes from the entire calendar year, differences in the index value can be observed throughout the seasons. As indicated in studies [46-48] the resistances associated with the movement of the belt on the idler set increase with decreasing ambient temperature, increasing the energy consumption coefficient. The monthly SEC index graph shown in Fig. 8 indicates that its values vary across the seasons. It was assumed that spring months are *March, April, and May*; summer: *June, July, and August*; autumn: *September, October, and November* while winter: *December, January, and February*. In terms of energy consumption, conveyors operate more efficiently in the spring (the average SEC equals 0.48 Wh/m^4) and summer (the average SEC equals 0.49 Wh/m^4) months than in the autumn (the average SEC equals 0.55 Wh/m^4) and winter ones (the average SEC equals 0.62 Wh/m^4).

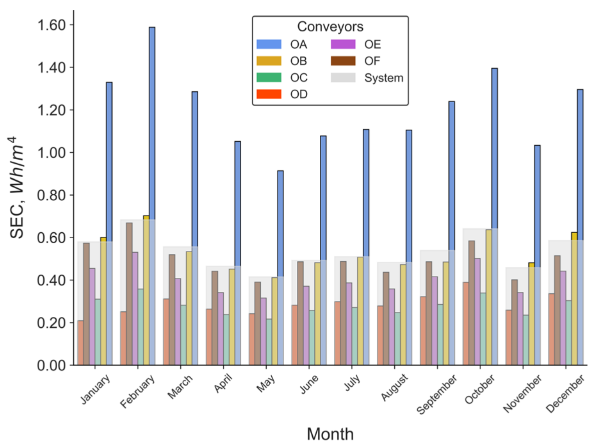


Fig. 8. Monthly values of specific energy consumption index for the analysed belt conveyors and the transportation system

Summarising the above analyses, it has been concluded that at this stage, a definitive assessment of the energy efficiency of belt conveyors based on the indicated specific energy consumption value is not possible. It has been demonstrated that incline conveyors exhibit a higher energy efficiency index, thus consuming more electrical energy than horizontal conveyors. It is caused due to the resistance encountered in lifting the material, which significantly alters the structure of conveyor motion resistances and has been identified as a significant parameter for further specific energy consumption index analysis.

To mitigate the impact of lifting resistances resulting from the necessity of fulfilling the transportation task, it was decided to subtract the energy required to overcome the elevation height. Although this procedure requires an analytical determination of these resistances, which does not always lead to results close to reality; this approach allows treating all conveyors as horizontal and facilitates a rational comparison of their energy consumption. For the calculation of the lifting energy, it was assumed that the ratio of elevation height to conveyor length equals the sine of the conveyor incline angle, and the density of the material was assumed to be 1,700 kg/m^3.

The obtained results of the modified specific energy consumption index distribution are shown in Fig. 9 and Fig. 10. It can be noticed that the index values for conveyor OA underwent a significant decrease – the average specific energy consumption value decreased by approximately 42% compared to the pre-modification values. However, the values for the incline conveyor are still higher than for the other conveyors, especially for small, transported volumes. This is because, in the case of incline conveyors operating with low load, the conveyor drive operates in a low-efficiency range.

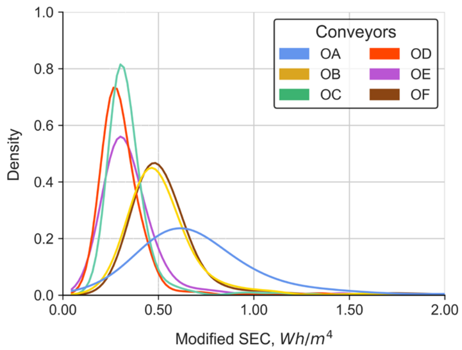


Fig. 9. The probability density function of the modified specific energy consumption index for analysed belt conveyors

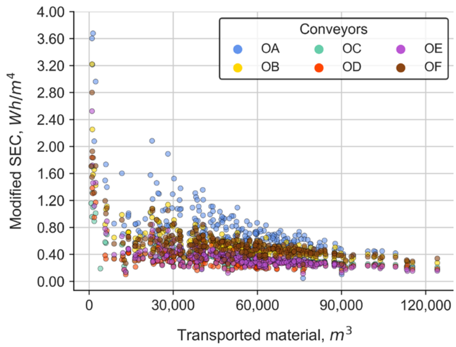


Fig. 10. Relationship between daily modified specific energy consumption index and the daily transported amount of the material

3. The idea of energy efficiency class determination

The idea is to use the modified specific energy consumption index and the transported overburden volume as key parameters to identify groups similar to each other in terms of conveyor energy efficiency. For this purpose, the k-means clustering algorithm was used. The algorithm works by identifying clusters (or groups) and comparing the distances between their geometric centres (centroids) and individual observations. The objective of the iterative k-means algorithm is to minimise the sum of squares of distances between points and cluster centroids [49]. The algorithm works as follows:

1. Initialization
   - Choose the number of clusters,
   - Initialise the cluster centroids.
2. Iterative Optimization
   - Assign data point x_i to cluster j, which is defined as:

$$C_i = \arg\min \|x_i - \mu_j\|^2 \tag{2}$$

where:

$\|x_i - \mu_j\|^2$ – the squared Euclidean distance between the data point x_i and the cluster centroid μ_j,

C_i – the index of the cluster assigned to the i -th data point.

   - Recompute cluster centroids based on the current assignment of data points. The update rule for each centroid μ_j is:

$$\mu_j = \frac{1}{|C_j|}\sum_{i \in j} x_i \tag{3}$$

where:

C_j – the set of data points assigned to cluster j,

$|C_j|$ – the number of points in cluster j,

x_i – the data points in cluster j.

3. Objective Function

$$J = \sum_{j=1}^{K}\sum_{i \in C_j} x_i - \mu_j{}^2 \tag{4}$$

where:

J – the total within cluster variance,

K – the number of clusters,

C_j – the set of points in cluster j,

x_i – the data points in cluster j,

μ_j – the centroid of cluster j.

To evaluate the performance of the clustering algorithm the Silhouette score was used. It measures how similar a data point is to its cluster compared to other clusters. Silhouette score is calculated using the formula:

$$s_i = \frac{b_i - a_i}{\max(b_i, a_i)} \tag{5}$$

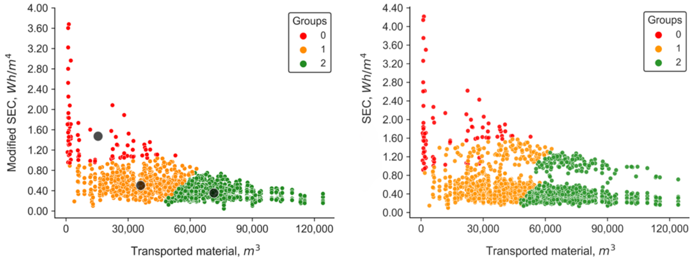
where:

s_i – the silhouette score,

b_i – the mean nearest-cluster distance,

a_i – the mean intra-cluster distance.

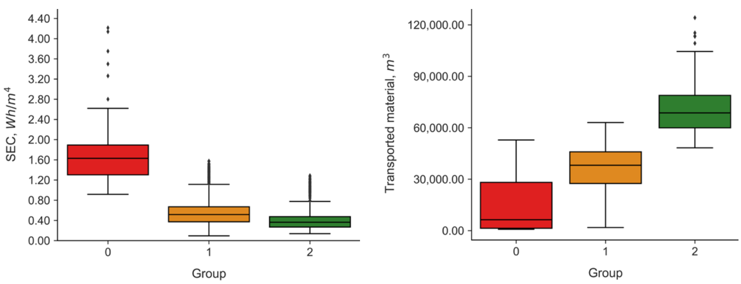
The highest value of the Silhouette index was achieved for 3 clusters. Therefore, the dataset was divided into 3 groups indicating different patterns of conveyor transport potential usage and various levels of energy efficiency index values concerning the 24-hour period. The result of clustering on data with the modified specific energy consumption index is shown in Fig. 11a, where the centres of the designated clusters are marked in black colour. At this stage, the generated groups 0, 1, and 2 can be associated with energy efficiency classes, named accordingly as high, medium, and low energy efficiency classes (Fig. 11b).



a) b)

Fig. 11. The result of clustering shown as a relationship between a) the modified daily specific energy consumption index, b) the daily specific energy consumption index and the volume of transported material

The least populous group is group 0. Approximately 5% of all observations are classified there, among which about 50% are attributed to conveyor OA. The small size of group 0 contains observations that could be considered outliers in the initial phase of analysis. In the remaining groups, namely 1 and 2, there are 45% and 50% of all observations, respectively. Concerning conveyor OA, approximately 15% of observations were assigned to group 0. However, the remaining conveyors represent individual observations in this group. It was also noticed that over 50% of observations for conveyors OC, OD, and OF were classified into group 2. The quality of the conducted clustering was evaluated using box plots (Fig. 12) and the median value for the daily energy efficiency index and transported material volume in the designated groups 0, 1, and 2. The obtained results indicate differences in the values of the feature location measures in the considered groups, thus demonstrating sufficient quality of the conducted separation.



a) b)

Fig. 12. Box plot distribution of values a) for the daily specific energy consumption index b) transported volume over the course of the day in respective energy efficiency groups

The conducted clustering process allowed for the identification of energy efficiency classes of belt conveyors and their energy efficiency level comparison within the analysed dataset range. However, due to the limited range of measurement data, direct normalisation of energy efficiency class thresholds was not feasible.

Obtained results have shown that ascending conveyors can be assessed as energy-efficient ones and that a low SEC index value does not always indicate an energy-efficient conveyor. It seems that the key point is the amount of the transported material or more precisely, the material load parameter. The parameter defined as the ratio of actual throughput to maximum throughput allows for relating the achieved performance during operation to the degree of utilisation of installed drive power. This way the use of the conveyor's transport potential or its effective utilisation will be taken into consideration while assessing belt conveyor energy efficiency; especially valuable when comparing conveyors operating in different transport lines.

4. Conclusions

In summary, based on the presented in the paper analyses and obtained results the following observations have been noted.

- The level of electricity consumption is not a measure that objectively allows for the assessment of the energy efficiency of belt conveyors.
- The specific energy consumption index (SEC) is a relevant parameter but itself does not constitute a universal tool for assessing the energy efficiency of belt conveyors.
- Energy efficiency assessment should particularly cover the issue of operational efficiency, which means that:
  - the evaluation of operational efficiency should consider the inclination angle of the conveyor route due to its influence on changing the structure of conveyor resistances.
  - the assessment of operational efficiency should consider the utilisation of the conveyor's transport potential by determining the degree of its nominal throughput usage.

The analyses conducted above do not allow for direct normalisation of energy efficiency class thresholds based on measurement data. Hence, there is a need to attempt to delineate energy efficiency classes using a dataset that encompasses the full range of all considered parameters. This will enable the determination of a reference value for energy intensity within a specific group of conveyors, ultimately leading to the proper classification of energy classes. Furthermore, energy classes should be determined individually, depending on the range of conveyor inclination angle and load distribution, as these two parameters have been identified as crucial in the attempts to assess the energy efficiency of belt conveyors. This means that the final classification should be based on the SEC index value, which will achieve different threshold values for different incline and load categories. Therefore, the scheme shown in Fig. 2 can be adjusted to show steps that lead to the proper assessment of the energy efficiency of belt conveyors (Fig. 13).

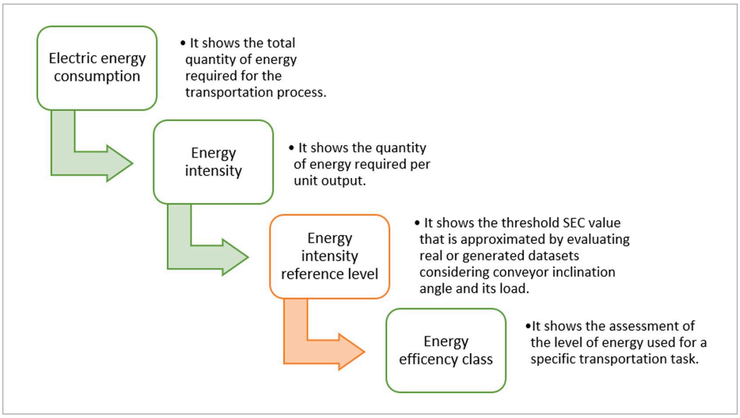


Fig. 13. Scheme of belt conveyors energy efficiency assessment

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